

# Gamma rays from cloud penetration at the base of AGN jets

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## ABSTRACT

**Context.** Dense and cold clouds seem to populate the broad line region surrounding the central black hole in AGNs. These clouds could interact with the AGN jet base and this could have observational consequences.

**Aims.** We want to study the gamma-ray emission produced by these jet-cloud interactions, and explore under which conditions this radiation would be detectable.

**Methods.** We investigate the hydrodynamical properties of jet-cloud interactions and the resulting shocks, and develop a model to compute the spectral energy distribution of the emission generated by the particles accelerated in these shocks. We discuss our model in the context of radio-loud AGNs, with applications to two representative cases, the low-luminous Centaurus A, and the powerful 3C 273.

**Results.** Some fraction of the jet power can be channelled to gamma-rays, which would be likely dominated by synchrotron self-Compton radiation, and show typical variability timescales similar to the cloud lifetime within the jet, which is longer than several hours. Many clouds can interact with the jet simultaneously leading to fluxes significantly higher than in one interaction, but then variability will be smoothed out.

**Conclusions.** Jet-cloud interactions may produce detectable gamma-rays in non-blazar AGNs, of transient nature in nearby low-luminous sources like Cen A, and steady in the case of powerful objects of FR II type.

**Key words.** quasars: general – radiation mechanisms: non-thermal – gamma-rays: general

## 1. Introduction

Active galactic nuclei (AGN) consist of an accreting super-massive black hole (SMBH) in the center of a galaxy and sometimes present powerful radio emitting jets (Begelman et al. 1984). Radio-loud AGNs have continuum emission along the whole electromagnetic spectrum, from radio to gamma rays (e.g. Boettcher 2007). This radiation basically comes from the accretion disc and bipolar relativistic jets originated close to the central SMBH. Radiation of accretion origin can be produced by the thermal plasma of either an optically-thick geometrically-thin disc under efficient cooling (Shakura & Sunyaev 1973), or an optically-thin geometrically-thick corona (e.g. Liang & Thompson 1979). The emission from the jets is non-thermal and generated by a population of relativistic particles likely accelerated in strong shocks, although other mechanisms are also possible (Rieger et al. 2007). This non-thermal emission is thought to be produced through synchrotron and inverse Compton (IC) processes (e.g. Ghisellini et al. 1985), although hadronic models have been also considered to explain gamma-ray detections (e.g. Mannheim 1993, Mücke & Protheroe 2001, Aharonian 2002).

In addition to continuum radiation, AGNs also present optical and ultra-violet lines. Some of these lines are broad,

emitted by gas moving with velocities  $v_g > 1000 \text{ km s}^{-1}$  and located in a small region close to the SMBH, the so-called broad line region (BLR). The structure of this region is not well known but some models assume that the material in the BLR could be formed by dense clouds confined by a hot ( $T \sim 10^8 \text{ K}$ ) external medium (Krolik et al. 1981) or by magnetic fields (Rees 1987). These clouds would be ionized by photons from the accretion disc producing the observed emission lines, which are broad because of the cloud motion within the SMBH potential well. An alternative model proposes that the broad lines are produced in the chromosphere of evolved stars (Penston 1988) present in the nuclear region of AGNs.

The presence of material surrounding the base of the jets in AGNs makes jet-medium interactions likely. For instance, the interaction of BLR clouds with a jet in AGNs was already suggested by Blandford & Königl (1979) as a mechanism for knot formation in the radio galaxy M87. Also, the gamma-ray production due to the interaction of a cloud from the BLR with a proton beam or a massive star with a jet were studied in the context of AGNs by Dar & Laor (1997) and Bednarek & Protheroe (1997), respectively.

In this work, we study the interaction of BLR clouds with the innermost jet in an AGN and its observable consequences at high energies. The approach adopted is similar to that followed in Araudo et al. (2009) for high-mass microquasars (for a general comparison between these sources and AGNs see Bosch-Ramon 2008), where the interaction

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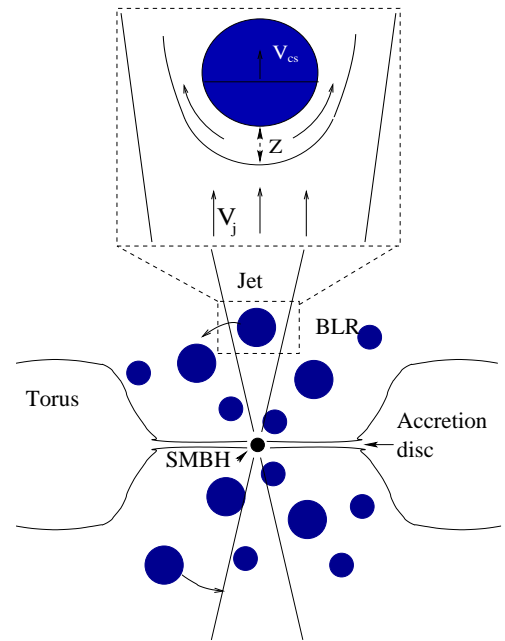
of stellar wind clumps of the companion star with the microquasar jet was studied. Under magnetic fields below equipartition with the jet kinetic energy (i.e. the jet should be matter dominated), cloud penetration will lead to the formation of a relativistic bow shock in the jet and a slow shock inside the cloud. Electrons and protons can be efficiently accelerated in the bow shock and produce non-thermal emission, in situ via synchrotron and synchrotron self-Compton (SSC) mechanism, and in the cloud through proton-proton ( $pp$ ) collisions. For magnetic fields well below equipartition, the SSC component becomes the dominant electron cooling channel, that leads to significant gamma-ray production. Since the bow shock downstream is almost at rest in the laboratory reference frame (RF), this emission will not be significantly boosted. The resulting spectrum and the achieved luminosities in one jet-cloud interaction depend strongly on the magnetic field, the location of the interaction region, the cloud size, and the jet luminosity. However, many clouds could be inside the jet simultaneously, and then the BLR global properties, like size and total number of clouds, would also be relevant. Depending on whether one cloud or many of them penetrate into the jet, the lightcurve will be flare-like or rather steady, respectively.

In order to explore the radiative outcomes of jet-cloud interactions in AGNs, we apply our model to both Faranoff-Riley galaxies I (FR I) and II (FR II). In particular, we consider Centaurus A (Cen A) and 3C 273, the nearest FR I and a close and very bright flat spectrum radio quasar (with FR II as parent population), as illustrative cases. Although in FR I the BLR is not well-detected, clouds with similar characteristics to those found in FR II galaxies may surround the SMBH (Wang et al. 1986, Risaliti 2009). Cen A has been detected at high- (HE) (Hartman et al. 1999; Abdo et al. 2010) and very high-energy (VHE) gamma rays (Aharonian et al. 2009), whereas 3C 273 has been detected so far only at HE gamma rays (Hartman et al. 1999; Abdo et al. 2010). We have computed the contribution of jet-cloud interactions to the gamma-ray emission in these sources, and estimated the gamma-ray luminosity in a wide range of cases. We find that gamma rays from jet-cloud interactions could be detectable by present and future instrumentation in nearby low-luminous AGNs at HE and VHE, and for powerful and nearby quasars only at HE, since the VHE radiation is absorbed by the dense nuclear photon fields. In the case of sources showing boosted gamma rays (blazars), the isotropic radiation from jet-cloud interactions will be masked by the jet beamed emission, which will not be the case in non-blazar sources.

The paper is organized as follows: in Sect. 2, the dynamics of jet-cloud interactions is described; in Sect. 3, a model for particle acceleration and emission is presented for one interaction, whereas in Sect. 4 the case of many clouds interacting with the jet is considered; in Sects. 5 and 6, the model is applied to FR I and FR II galaxies, focusing on the sources Cen A and 3C 273; finally, in Sect. 7, the results of this work are summarized and discussed. We adopt cgs units through-out the paper.

## 2. The jet-cloud interaction

Under certain combinations of the jet ram pressure, and the cloud size and density, cloud-jet penetration is expected to occur. The details of the penetration process itself are com-



**Fig. 1.** Sketch, not to scale, of an AGN at the spatial scales of the BLR region. In the top part of the figure, the interaction between a cloud and the jet is also shown.

**Table 1.** Values assumed in this work for BLR clouds and jets.

Description	Value
Cloud size	$R_c = 10^{13}$ cm
Cloud density	$n_c = 10^{10}$ cm $^{-3}$
Cloud velocity	$v_c = 10^9$ cm s $^{-1}$
Cloud temperature	$T_c = 2 \times 10^4$ K
Jet Lorentz factor	$\Gamma = 10$
Jet half-opening angle	$\phi \approx 6^\circ$

plex. Here we do not treat them in detail, but just assume that penetration occurs if certain conditions are fulfilled. For low magnetic fields, a cloud inside the jet may represent a hydrodynamic situation in which a supersonic flow interacts with a body of approximately spherical shape at rest. The cloud, as long as it has not been accelerated by the jet ram pressure up to the jet speed ( $v_j$ ), produces a perturbation in the jet medium in the form of a steady bow shock roughly at rest in the laboratory RF, with a velocity with respect to the jet RF approximately equal to  $v_j$ . Since the cloud is not rigid, a wave propagates also through it. Since the cloud temperature is much lower, and the density much higher than in the jet, this wave will be still supersonic but much slower than the bow shock. The jet pressure exerts a force on the cloud leading to cloud acceleration along the axis, hydrodynamical instabilities and, eventually, cloud fragmentation. In the following, the jet-cloud interaction is described. Further discussion, and a proper account of the literature, can be found in Araudo et al. (2009). Sketches of the jet-cloud interaction and the jet-BLR scenario are shown in Fig. 1.

We adopt here clouds with typical density  $n_c = 10^{10}$  cm $^{-3}$  and size  $R_c = 10^{13}$  cm (Risaliti 2009). The velocity of the cloud is taken  $v_c = 10^9$  cm s $^{-1}$  (Peterson 2006).

The jet Lorentz factor is fixed to  $\Gamma = 10$ , implying  $v_j \approx c$ , with a half-opening angle  $\phi \approx 6^\circ$ , i.e. the jet radius/height relation fixed to  $R_j = \tan(\phi) z = 0.1 z$ . All these parameters are summarized in Table 1 and will not change along the paper; from them, the jet density  $n_j$  in the laboratory RF can be estimated:

$$n_j = \frac{L_j}{(\Gamma - 1) m_p c^3 \sigma_j} \approx 8 \times 10^4 \left( \frac{L_j}{10^{44} \text{ erg s}^{-1}} \right) \times \left( \frac{\Gamma - 1}{9} \right)^{-1} \left( \frac{z}{10^{16} \text{ cm}} \right)^{-2} \text{ cm}^{-3}, \quad (1)$$

where  $\sigma_j = \pi R_j^2$  and  $L_j$  is the kinetic power of the matter dominated jet.

The jet ram pressure should not destroy the cloud before it has fully entered into the jet. This means that the time required by the cloud to penetrate into the jet should be:

$$t_c \sim \frac{2R_c}{v_c} = 2 \times 10^4 \left( \frac{R_c}{10^{13} \text{ cm}} \right) \left( \frac{v_c}{10^9 \text{ cm s}^{-1}} \right)^{-1} \text{ s}, \quad (2)$$

should be shorter than the cloud lifetime inside the jet. To estimate this cloud lifetime, let us compute first the time required by the shock in the cloud to cross it ( $t_{cs}$ ). The velocity of this shock,  $v_{cs}$ , can be derived making equal the jet and the cloud shock ram pressures:  $(\Gamma - 1) n_j m_p c^2 = n_c m_p v_{cs}^2$ , valid as long as  $v_{cs} \ll c$ . Then:

$$v_{cs} \sim \chi^{-1/2} c \sim 3 \times 10^8 \left( \frac{n_c}{10^{10} \text{ cm}^{-3}} \right)^{-1/2} \times \left( \frac{z}{10^{16} \text{ cm}} \right)^{-1} \left( \frac{L_j}{10^{44} \text{ erg s}^{-1}} \right)^{1/2} \text{ cm s}^{-1}, \quad (3)$$

where  $\chi$  is the cloud to jet density ratio,  $n_c/n_j(\Gamma - 1)$ . This yields a cloud shocking time:

$$t_{cs} \sim \frac{2R_c}{v_{cs}} \simeq 7 \times 10^4 \left( \frac{R_c}{10^{13} \text{ cm}} \right) \left( \frac{n_c}{10^{10} \text{ cm}^{-3}} \right)^{1/2} \times \left( \frac{z}{10^{16} \text{ cm}} \right) \left( \frac{L_j}{10^{44} \text{ erg s}^{-1}} \right)^{-1/2} \text{ s}. \quad (4)$$

Therefore, for a penetration time ( $t_c$ ) at least as short as  $\sim t_{cs}$ , the cloud will remain being an effective obstacle for the jet flow. Setting  $t_c \sim t_{cs}$ , we obtain a minimum value for  $\chi$  and hence for  $z$ .

Hydrodynamical instabilities produced by the interaction with the jet material will affect the cloud. First of all, the jet exerts a force on the cloud through the contact discontinuity. The acceleration applied to the cloud can be estimated from the jet ram pressure  $P_j$ , and the cloud section  $\sigma_c \sim \pi R_c^2$  and mass  $M_c \sim (4/3) \pi R_c^3 n_j m_p$ :

$$g = \frac{P_j \sigma_c}{M_c} \sim \frac{3}{4} \frac{c^2}{\chi R_c} = \frac{3}{2} \frac{v_{cs}}{t_{cs}}. \quad (5)$$

Given the acceleration exerted by the jet in the cloud, Rayleigh-Taylor (RT) instabilities will develop in the cloud, at the jet contact discontinuity, with timescale:

$$t_{RT} \sim \sqrt{\frac{l}{g}} = \sqrt{\frac{4\chi l R_c}{3c^2}}, \quad (6)$$

where the instability length  $l$  is the spatial scale of the perturbation. For perturbations of the size of the cloud:  $l \sim R_c$ ,

which are those associated to cloud significant disruption, one gets  $t_{RT} \sim t_{cs}$ .

In addition to RT instabilities, Kelvin-Helmholtz (KH) instabilities also grow in the cloud walls in contact with shocked jet material that surrounds the cloud. Accounting for the high relative velocity,  $v_{rel} \lesssim v_j$ , one obtains:

$$t_{KH} \gtrsim \sqrt{\frac{l}{g_{rel}}} = \frac{\chi l}{c}, \quad (7)$$

where  $g_{rel} \sim c^2/\chi l$ . For  $l \sim R_c$ , we obtain  $t_{KH} \gtrsim t_{cs}$ . In the previous estimates of  $t_{RT}$  and  $t_{KH}$  we have not taken into account the effect of the magnetic field (e.g. Blake 1972), since we assume that it is dynamically negligible. We note that, given  $g$ , the time to accelerate the cloud up to the shock velocity  $v_{cs}$  is  $\sim t_{cs}$ . However, the timescale to accelerate the cloud up to  $v_j$  is  $\gg t_{cs}$  provided that  $v_j \gg v_{cs}$ , and before, the cloud will likely fragment.

Finally, there are two additional timescales also relevant for our study, the bow-shock formation time,  $t_{bs}$ , and the time required by the cloud to cross the jet,  $t_j$ . The timescale  $t_{bs}$  can be roughly estimated assuming that the shock downstream has a cylindrical shape with one of the bases being the bow shock, relativistic shock jump conditions, equal particle injection and escape rates, and a escape velocity similar to the sound speed  $\sim c/\sqrt{3}$  (for a relativistic plasma). This yields a shock-cloud separation distance of  $Z \sim 0.3 R_c$ , which implies:

$$t_{bs} \sim \frac{Z}{c} = 10^2 \left( \frac{R_c}{10^{13} \text{ cm}} \right) \text{ s}. \quad (8)$$

Since in general  $t_{bs} \ll t_{cs}$ , we can assume that the bow shock is in the steady regime. The jet crossing time  $t_j$  can be characterized by:

$$t_j \sim \frac{2R_j}{v_c} = 2 \times 10^6 \left( \frac{z}{10^{16} \text{ cm}} \right) \left( \frac{v_c}{10^9 \text{ cm s}^{-1}} \right)^{-1} \text{ s}. \quad (9)$$

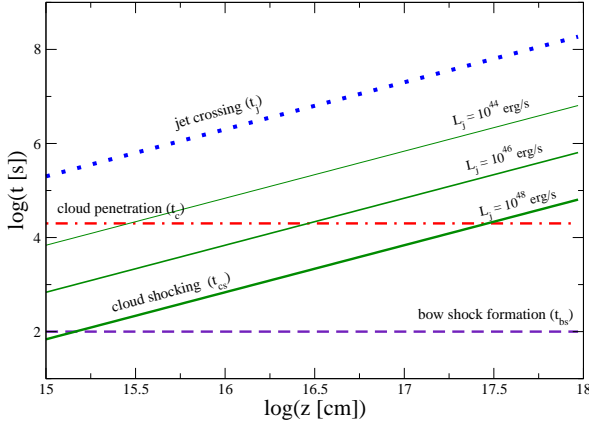
Note that if the cloud lifetime is  $< t_j$ , the number of clouds inside the jet will be smaller than expected just from the BLR properties.

In order to summarize the discussion of the dynamics of the jet-clump interaction, we plot in Fig. 2 the  $t_{cs}$  (for different  $L_j$ ),  $t_j$ ,  $t_c$ , and  $t_{bs}$  as a function of  $z$ . As shown in the figure, for some values of  $z$  and  $L_j$  the cloud could be destroyed by the jet before full penetration, i.e.  $t_{cs} < t_c$ . This is a constraint to determine the height  $z$  of the jet at which the cloud can penetrate into it. Note also that, in general,  $t_{bs}$  is much shorter than any other timescale.

## 2.1. The interaction height

The cloud can fully penetrate into the jet if the cloud lifetime after jet impact is longer than the penetration time (the weaker condition that jet lateral pressure is  $< n_c m_p v_c^2$  is then automatically satisfied). This determines the minimum interaction height,  $z_{int}$ , to avoid cloud disruption before full penetration. Also, this interaction cannot occur below the jet formation region,  $z_0 \sim 100 R_g \approx 1.5 \times 10^{15} (M_{bh}/10^8 M_\odot) \text{ cm}$  (Junor et al. 1999). For BLR-jet interaction and cloud penetration to occur, the size of the BLR should be  $R_{blr} > z_0$  and  $z_{int}$ .

The lifetime of the cloud depends on the fragmentation time, which is strongly linked to, but longer than,  $t_{cs}$ .



**Fig. 2.** The jet crossing (blue dotted line), cloud penetration (red dot-dashed line), bow-shock formation (violet dashed line) and cloud shocking (green solid lines) times are plotted; all of them have been calculated using the values given in Table 1. The time  $t_{cs}$  is plotted for  $L_j = 10^{44}$ ,  $10^{46}$  and  $10^{48}$  erg s $^{-1}$ .

The value of  $z_{int}$  can be estimated then setting  $t_c \lesssim t_{cs}$ , since the cloud should enter the jet before being significantly distorted by the impact of the latter. Once shocked, the cloud can suffer lateral expansion and conduction heating, which can speed up fragmentation due to instabilities. In this work, we choose  $z_{int}$  fixing  $t_{cs} = 2t_c$ :

$$z_{int} \approx 5 \times 10^{15} \left( \frac{v_c}{10^9 \text{ cm s}^{-1}} \right)^{-1} \left( \frac{n_c}{10^{10} \text{ cm}^{-3}} \right)^{-1/2} \times \left( \frac{L_j}{10^{44} \text{ erg s}^{-1}} \right)^{1/2} \text{ cm.} \quad (10)$$

We note that the available power in the bow shock is  $L_{bs} \sim (\sigma_c/\sigma_j) L_j \propto z^{-2}$ . Therefore, the most luminous individual jet-cloud interaction will take place at  $z \sim z_{int}$ .

The BLR size can be estimated through an empirical relation obtained from sources with a well established BLR, i.e. FR II radio galaxies. This relation is in general of the type  $R_{blr} \propto L_{blr}^\alpha$ , where  $L_{blr}$  is the luminosity of the BLR and  $\alpha \sim 0.5 - 0.7$  (e.g. Kaspi et al. 2005, 2007; Peterson et al. 2005; Bentz et al. 2006). In this paper we use the following relations:

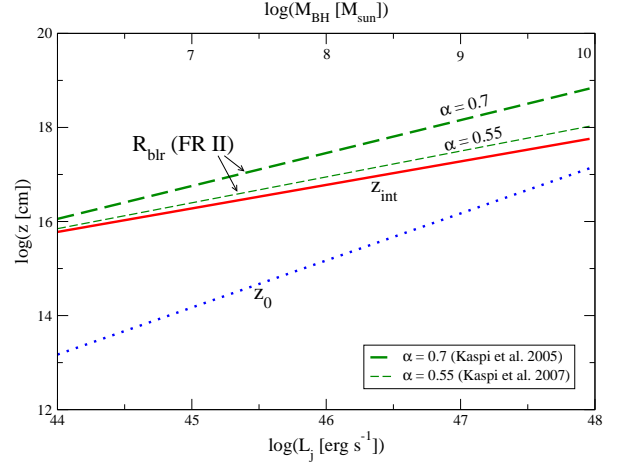
$$R_{blr} \sim 6 \times 10^{16} \left( \frac{L_{blr}}{10^{44} \text{ erg s}^{-1}} \right)^{0.7} \text{ cm,} \quad (11)$$

and

$$R_{blr} \sim 2.5 \times 10^{16} \left( \frac{L_{blr}}{10^{44} \text{ erg s}^{-1}} \right)^{0.55} \text{ cm,} \quad (12)$$

from Kaspi et al. (2005, 2007).

In Fig. 3 we show the relation of  $z_{int}$  and  $R_{blr}$  with  $L_j$ , assuming that  $L_{blr}$  is a 10% of the disc luminosity, which is taken here equal to  $L_j$ . As seen in the figure, for reasonable parameters, the condition  $z_{int} < R_{blr}$  is fulfilled for a wide range of  $L_j$ . Figure 3 also shows the relation between  $z_0$  and  $M_{bh}$ , which shows that for  $M_{bh} \gtrsim 10^9 M_\odot$  the jet could be



**Fig. 3.** The interaction height,  $z_{int}$  (red solid line), and the size of the BLR,  $R_{blr}$  (green dashed line), for different values of  $L_j$  (bottom horizontal axis). We have derived  $R_{blr}(L_j)$  fixing  $L_{blr} = 0.1 L_j$  and plotted  $R_{blr}$  using Eqs. (11) and (12). In the same plot, the height of the jet base,  $z_0$  (blue dotted line), is plotted as a function of  $M_{BH}$  (top horizontal axis).

even not (fully) formed at the BLR scales at the lowest  $L_j$ -values.

### 3. Non-thermal particles and their emission

In the bow and cloud shocks, particles can be accelerated through diffusive shock acceleration (Bell 1978). However, the bow shock should be more efficient accelerating particles than the shock in the cloud because  $v_{bs} \gg v_{cs}$ . In addition, the cloud shock luminosity is smaller than the bow-shock luminosity by  $\sim 1/(2\chi^{1/2})$ . For these reasons, we focus here on the particle acceleration in the bow shock. In this section, we briefly describe the injection and evolution of particles, and their emission, remarking those aspects that are specific to AGNs. The details of the emitting processes considered here (synchrotron, IC and  $pp$  interactions) can be found in Araudo et al. (2009) and references therein.

First, one can estimate the non-thermal luminosity,  $L_{nt}$ , injected at  $z_{int}$  in the bow shock in the form of relativistic electrons or protons:

$$L_{nt} = \eta_{nt} L_{bs} \approx 4 \times 10^{39} \left( \frac{\eta_{nt}}{0.1} \right) \left( \frac{R_c}{10^{13} \text{ cm}} \right)^2 \times \left( \frac{L_j}{10^{44} \text{ erg s}^{-1}} \right) \text{ erg s}^{-1}. \quad (13)$$

Then, the accelerator/emitter magnetic field in the bow-shock RF ( $B$ ) can be determined relating  $U_B = \eta_B U_{nt}$ , where  $U_B = B^2/8\pi$  and  $U_{nt} = L_{nt}/(\sigma_c c)$  are the magnetic and the non-thermal energy densities, respectively. For leptonic emission and to avoid suppression of the IC channel, high gamma-ray outputs require  $\eta_B$  well below 1. In this context,  $B$  can be parametrized as follows:

$$B \approx 10 \left( \frac{\eta_B}{0.01} \right) \left( \frac{v_c}{10^9 \text{ cm s}^{-1}} \right)^2 \left( \frac{n_c}{10^{10} \text{ cm}^{-3}} \right) \text{ G.} \quad (14)$$

Regarding the acceleration mechanism, since the bow shock is relativistic and the treatment of such a shocks is complex (see Achterberg et al. 2001), we adopt the following prescription for the acceleration rate:

$$\dot{E}_{\text{acc}} = 0.1 q B c, \quad (15)$$

similar to that in the relativistic termination shock of the Crab pulsar wind (de Jager et al. 1996).

Particles suffer different losses that balance the energy gain from acceleration. The electron loss mechanisms are escape downstream, relativistic Bremsstrahlung, synchrotron emission, and external Compton (EC) and SSC. We note that  $B$ ,  $L_{\text{nt}}$  and the accelerator/emitter size at  $z_{\text{int}}$  are constant for different  $L_j$  and fixed  $\eta_B$  and  $\eta_{\text{nt}}$ , and only  $L_{\text{blr}}$  and  $L_d$  are expected to change with  $L_j$ . Therefore, as long as the external photon fields are negligible, the maximum electron energy at  $z_{\text{int}}$  does not change for different jet powers.

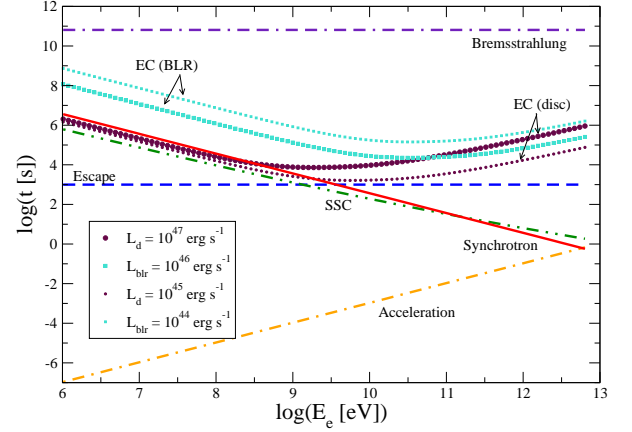
In Fig. 4, the leptonic cooling timescales are plotted together with the escape time and the acceleration time for a bow shock located at  $z_{\text{int}}$ . A value for  $\eta_B$  equal to 0.01 has been adopted. The SSC cooling timescale is plotted for the steady state. The escape time downstream the relativistic bow shock is taken as:

$$t_{\text{esc}} \sim \frac{3 R_c}{c} = 10^3 \left( \frac{R_c}{10^{13} \text{ cm}} \right) \text{ s}. \quad (16)$$

Synchrotron and EC/SSC are the dominant processes in the high-energy part of the electron population, relativistic bremsstrahlung is negligible for any energy, and electron escape is relevant in the low-energy part. This yields a break in the electron energy distribution at the energy at which the synchrotron/IC time and the escape time are equal. The Thomson to KN transition is clearly seen in the EC cooling curves, but is much smoother in the SSC case. The maximum electrons energy are around several TeV. Given the similar cooling timescale for electrons via relativistic bremsstrahlung and protons through  $pp$  collisions ( $t_{\text{brems/pp}} \sim 10^{15}/n$  s, where  $n$  is the target density), protons will not cool efficiently in the bow shock. Photomeson production can also be discarded as a relevant proton cooling mechanism in the bow shock due to the relatively low achievable proton energies and photon densities. The maximum proton energy of protons is constrained making equal the acceleration time and the time needed to diffuse out of the bow shock. Assuming Bohm diffusion,  $t_{\text{diff}} = 3 Z^2/2 r_g c$  (where  $r_g$  is the particle gyroradius), maximum proton energy is:

$$E_p^{\text{max}} \sim 0.1 q B R_c = 5 \times 10^3 \left( \frac{B}{10 \text{ G}} \right) \left( \frac{R_c}{10^{13} \text{ cm}} \right) \text{ TeV}. \quad (17)$$

Electrons are injected in the bow shock region following a power-law in energy of index 2.2 (Achterberg et al. 2001) with an exponential cutoff at the maximum electron energy. The injection luminosity is  $L_{\text{nt}}$ . To first order, the electron evolution can be computed assuming homogeneous conditions, following therefore a one-zone approximation with all the mentioned cooling and escape processes. The formulae for all the relevant radiative mechanisms, as well as the solved electron evolution differential equation, can be found in Araudo et al. (2009). In some cases, SSC is the dominant cooling channel at high energies. In that case, the calculations have to be done numerically splitting the



**Fig. 4.** Acceleration gain (orange dot-dashed line), escape (blue dashed line) and cooling lepton timescales are plotted. SSC (green two-dot-dashed line) is plotted when the steady state is reached and EC for the both BLR (turquoise square line) and disc (maroon dotted line) photon fields are shown for the conditions of faint (BLR:  $10^{44}$ ; disc:  $10^{45}$  erg s $^{-1}$ ) and bright sources (BLR:  $10^{46}$ ; disc:  $10^{47}$  erg s $^{-1}$ ). Synchrotron (red solid line) and relativistic Bremsstrahlung (violet dot-two-dashed line) are also plotted. We have fixed here  $\eta_B = 0.01$ . For protons, the  $pp$  cooling timescale is not shown for clarity, although it would be similar to that of relativistic bremsstrahlung.

evolution of the electron population in different time steps. In each step, the radiation field is updated accounting for the synchrotron emission produced in the previous step until the steady state is reached. The duration of each step should be shorter for the earlier phases of the evolutionary state to account properly for the rise of the synchrotron energy density in the emitter.

Once the steady-state electron distribution in the bow shock is computed, the spectral energy distribution (SED) of the non-thermal radiation can be calculated. The synchrotron self-absorption effect has to be taken into account, which will affect the low energy band of the synchrotron emission. At gamma-ray energies, photon-photon absorption due to the disc and the BLR radiation are to be considered, the internal absorption due to synchrotron radiation being negligible. Given the typical BLR and disc photon energies,  $\sim 10$  eV and  $\sim 1$  keV, respectively, gamma rays beyond 1 GeV and 100 GeV can be strongly affected by photon-photon absorption. On the other hand, for most of cases photons between 100 MeV and 1 GeV energies will escape the dense disc photon field.

Although proton cooling is negligible in the bow-shock region, it may be significant in the cloud. Protons can penetrate into the cloud if  $t_{\text{esc}} > t_{\text{diff}}$ , which yields a minimum energy to reach the cloud of  $E_p \sim 0.4 E_p^{\text{max}}$ . These protons will radiate in the form of gamma rays only a fraction  $\sim 3 \times 10^{-4} (R_c/10^{13} \text{ cm})(t_{\text{pp}}/10^5 \text{ s})^{-1}$  of their energy, which makes the process rather inefficient. The reason is that these protons cannot be efficiently confined and cross the cloud at a velocity  $\sim c$ . For further details of the proton energy distribution in the cloud, see Araudo et al. (2009).



#### 4. Many clouds inside the jet

Clouds fill the BLR, and many of them can simultaneously be inside the jet at different  $z$ , each of them producing non-thermal radiation. Therefore, the total luminosity can be much larger than the one produced by just one interaction, which is  $\sim L_{\text{nt}}$ . The number of clouds within the jets, at  $z \leq R_{\text{blr}}$ , can be computed from the jet ( $V_j$ ) and cloud ( $V_c$ ) volumes, resulting in:

$$N_c^j = 2f \frac{V_j}{V_c} \sim 9 \left( \frac{L_j}{10^{44} \text{ erg s}^{-1}} \right)^2 \left( \frac{R_c}{10^{13} \text{ cm}} \right)^{-3}, \quad (18)$$

where the factor 2 accounts for the two jets and  $f \sim 10^{-6}$  is the filling factor of clouds in the whole BLR (Dietrich et al. 1999). Actually,  $N_c^j$  is correct if one neglects that the cloud disrupts and fragments, and eventually dilutes inside the jet. For instance, Klein et al. (1994) estimated a shocked cloud lifetime in several  $t_{\text{cs}}$ , and Shin et al. (2008) found that even a weak magnetic field in the cloud can significantly increase its lifetime. Finally, even under cloud fragmentation, strong bow shocks can form around the cloud fragments before these have accelerated close to  $v_j$ . All this makes the real number of interacting clouds inside the jet hard to estimate, but it should be between  $(t_{\text{cs}}/t_j) N_c^j$  and  $N_c^j$ .

The presence of many clouds inside the jet, not only at  $z_{\text{int}}$  but also at higher  $z$ , implies that the total non-thermal luminosity available in the BLR-jet intersection region is:

$$L_{\text{nt}}^{\text{tot}} \sim 2 \int^{R_{\text{blr}}} \frac{dN_c^j}{dz} L_{\text{nt}}(z) dz \\ \sim 2 \times 10^{40} \left( \frac{\eta_{\text{nt}}}{0.1} \right) \left( \frac{R_c}{10^{13} \text{ cm}} \right)^{-1} \left( \frac{L_j}{10^{44} \text{ erg s}^{-1}} \right)^{1.7} \quad (19)$$

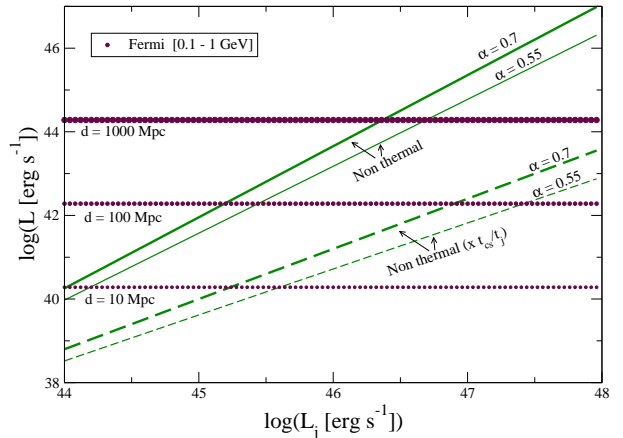
where  $dN_c^j/dz$  is the number of clouds located in a jet volume  $dV_j = \pi(0.1z)^2 dz$ . In both Eqs. 18 and 19,  $L_{\text{blr}}$  has been fixed to  $0.1 L_j$ , approximately as in FR II galaxies, and  $R_{\text{blr}}$  has been derived using Eq. (11).

In Fig. 5, we show estimates for the gamma-ray luminosity when many clouds interact simultaneously with the jet. For this, we have followed a simple approach assuming that most of the non-thermal luminosity goes to gamma rays. This will be the case as long as the escape and synchrotron cooling time are longer than the IC cooling time (EC+SSC) for the highest electron energies. Given the little information for the BLR in the case of FR I sources, we do not specifically consider these sources here.

In the two next sections, we present more detailed calculations applying the model presented in Sect. 3 to two characteristic sources, Cen A (FR I, one interaction) and 3C 273 (FR II, many interactions).

#### 5. Application to FR I galaxies: Cen A

Cen A is the closest AGN, with a distance  $d \approx 3.7$  Mpc (Israel 1998). It has been classified as an FR I radio galaxy and as a Seyfert 2 optical object. The mass of the black hole is  $\approx 6 \times 10^7 M_\odot$  (Marconi et al. 2000). The angle between the jets and the line of sight is large,  $> 50^\circ$  (Tingay et al. 1998), thus the jet radiation towards the observer should not suffer strong beaming. The jets of Cen A are disrupted at kpc scales, forming two giant radio lobes that extend  $\sim 10^\circ$  in the southern sky. At optical wavelengths,

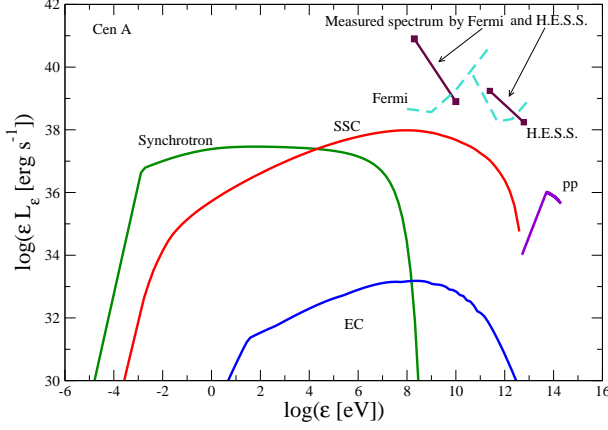


**Fig. 5.** Upper limits on the gamma-ray luminosity produced by  $N_c^j$  clouds inside the jet as a function of  $L_j$  in FR II sources. Two cases are plotted, one assuming that clouds cross the jet without disruption (green solid lines), and one in which the clouds are destroyed in a time as short as  $t_{\text{cs}}$  (green dashed lines). The thick (solid and dashed) and thin (solid and dashed) lines correspond to  $R_{\text{blr}} \propto L_{\text{blr}}^{0.7}$  (Kaspi et al. 2007) and  $R_{\text{blr}} \propto L_{\text{blr}}^{0.55}$  (Kaspi et al. 2005), respectively. In addition, the sensitivity levels of *Fermi* in the range 0.1–1 GeV (maroon dotted lines) are plotted for three different distances  $d = 10, 100$  and  $1000$  Mpc.

the nuclear region of Cen A is obscured by a dense region of gas and dust, probably as a consequence of a recent merger (Thomson 1992, Mirabel et al. 1999). At higher energies, *Chandra* and *XMM-Newton* detected continuum X-ray emission coming from the nuclear region with a luminosity  $\sim 5 \times 10^{41} \text{ erg s}^{-1}$  between 2–7 keV (Evans et al. 2004). These X-rays could be produced by the accretion flow and the inner jet, although their origin is still unclear. In the GeV range, Cen A was detected above 200 MeV by *Fermi*, with a bolometric luminosity of  $\approx 4 \times 10^{40} \text{ erg s}^{-1}$  (Abdo et al. 2009), and above  $\sim 200$  GeV by HESS, with a bolometric luminosity of  $\approx 3 \times 10^{39} \text{ erg s}^{-1}$  (Aharonian et al. 2009). In both cases, this HE emission is associated with the nuclear region. Cen A has been proposed to be a source of ultra HE cosmic rays (Romero et al. 1996).

A BLR has not been detected so far in Cen A (Alexander et al. 1999), although this could be a consequence of the optical obscuration produced by the dust lane. One can still assume that clouds surround the SMBH in the nuclear region (Wang et al. 1986, Risaliti et al. 2002) but, as a consequence of the low luminosities of the accretion disc, it is not expected that the photoionization of these clouds will be efficient enough to produce lines. Since no emission from these clouds is assumed, we only consider the EC scattering with photons from the accretion flow.

We adopt here a jet power for Cen A of  $L_j = 10^{44} \text{ erg s}^{-1}$ . From this value, and the values given in Sect. 2 for the remaining parameters of the jet and the cloud,  $z_{\text{int}}$  results in  $\approx 5 \times 10^{15} \text{ cm}$ . At this jet height, the emission produced by the interaction between one cloud and the jet is calculated assuming a  $\eta_B = 0.01$ , and the corresponding SED is presented in Fig. 6. As mentioned in Sect. 3, the low-



**Fig. 6.** Computed SED for one jet-cloud interaction at  $z_{\text{int}}$  in Cen A. We show also the SEDs of the detected emission by *Fermi* and HESS, as well as the sensitivity curves of these instruments.

**Table 2.** Adopted parameters for Cen A and 3C 273.

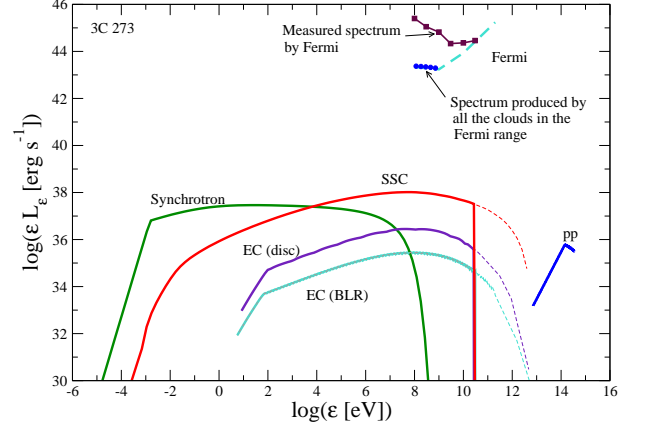
	Cen A	3C 273
Distance [Mpc]	3.7	$6.7 \times 10^2$
Black hole mass [ $M_{\odot}$ ]	$6 \times 10^7$	$7 \times 10^9$
Inclination angle [ $^{\circ}$ ]	$> 50$	$\sim 15$
Jet luminosity [ $\text{erg s}^{-1}$ ]	$10^{44}$	$4 \times 10^{47}$
Disc luminosity [ $\text{erg s}^{-1}$ ]	$5 \times 10^{41}$	$2 \times 10^{46}$
Disc photon energy* [eV]	$\sim 5 \times 10^3$	54
BLR luminosity $L_{\text{blr}}$ [ $\text{erg s}^{-1}$ ]	-	$4 \times 10^{45}$

\* of the thermal component.

energy band of the synchrotron spectrum is self-absorbed at energies below  $\sim 10^{-4}$  eV. At gamma-ray energies, photon-photon absorption is negligible due to the weak ambient photon fields (e.g. Rieger & Aharonian 2009, Araudo et al. 2009, 2010a,b). At high energies, SSC dominates the radiative output, with the computed luminosity above 100 MeV being  $\sim 2 \times 10^{39} \text{ erg s}^{-1}$ , and above 100 GeV about 10 times less. These luminosities are below the sensitivity of *Fermi* and HESS and one order of magnitude smaller than the observed ones. Note however that  $L_{\text{nt}} \propto R_c^2$ , and for slightly bigger clouds,  $L_{\text{nt}}$  may grow up to detectable levels. The penetration of a big clump in the base of the jet of Cen A would lead to a flare with a duration of about one day.

## 6. Application to FR II galaxies: 3C 273 (off-axis)

3C 273 is a powerful radio-loud AGN at a distance of  $d = 6.7 \times 10^2$  Mpc (Courvoisier 1998) with a SMBH mass  $M_{\text{BH}} \sim 7 \times 10^9 M_{\odot}$  (Paltani & Türler 2005). The angle of the jet with the line of sight is small,  $\approx 6^{\circ}$ , which implies the blazar nature of 3C 273 (Jolley et al. 2009). The whole spectrum of this source shows variability (e.g. Pian et al. 1999) from years (radio) to few hours (gamma rays). At high energies, 3C 273 was the first blazar AGN detected in the MeV band by the COS-B satellite and, later on, by



**Fig. 7.** Computed SED for one jet-cloud interaction at  $z_{\text{int}}$  in 3C 273. The emission in the 0.1–1 GeV range from many clouds inside the jet is also shown, together with the sensitivity level of *Fermi* and the observed SED above 200 MeV.

EGRET (Hartman et al. 1999). Recently, this source was also detected at GeV energies by *Fermi* and *AGILE*, but it has not been detected yet in the TeV range. Given the jet luminosity of 3C 273,  $L_j \approx 4 \times 10^{47} \text{ erg s}^{-1}$  (Kataoka et al. 2002),  $z_{\text{int}}$  results in  $\approx 3 \times 10^{17}$  cm. The BLR luminosity of this source is  $\approx 4 \times 10^{45} \text{ erg s}^{-1}$  (Cao & Jiang 1999), and its size  $7 \times 10^{17}$  cm (Ghissellini et al. 2010), which implies that jet-cloud interactions can take place. The disc luminosity is high,  $\approx 2 \times 10^{46} \text{ erg s}^{-1}$ , with typical photon energies  $\approx 54$  eV (Grandi & Palumbo 2004).

The non-thermal SED of the radiation generated by jet-cloud interactions in 3C 273 is shown in Fig. 7. At  $z_{\text{int}}$ , the most important radiative processes are synchrotron and SSC. The bolometric luminosities by these processes in one interaction at  $z_{\text{int}}$  are  $6 \times 10^{38} \text{ erg s}^{-1}$  and  $2 \times 10^{39} \text{ erg s}^{-1}$ , respectively. Given the presence of the strong radiation fields from the disc and the BLR, the emission above  $\sim 10$  GeV is absorbed through photon-photon absorption, and the maximum of the emission is around 0.1–1 GeV. Given the estimated number of clouds in the BLR of 3C 273,  $\sim 10^8$  (Dietrich et al. 1999), and the size is  $R_{\text{blr}} \approx 7 \times 10^{17}$  cm, the filling factor results in  $f \sim 3 \times 10^{-7}$ . With this value of  $f$ , the number of clouds in the two jets results in  $\sim 2 \times 10^3$  and  $5 \times 10^5$  for both the minimum and the maximum values (see Sect. 4). Considering the most optimistic case, the SSC luminosity would reach  $2 \times 10^{44} \text{ erg s}^{-1}$ . This value is well below the observed luminosity by *Fermi* in the GeV range,  $\sim 3 \times 10^{46} \text{ erg s}^{-1}$  in the steady state and  $\sim 1.7 \times 10^{47} \text{ erg s}^{-1}$  in flare (Soldi et al. 2009). However, the detected emission is very likely of beamed origin and should mask any unbeamed radiation. However, powerful non-blazar AGNs (FR II galaxies) do not present this beamed component, which makes possible the detection of GeV emission from jet-cloud interactions in these sources. In this case, given that many BLR clouds can interact with the jet simultaneously, the radiation should be steady.

## 7. Summary and discussion

In this work, the interaction of clouds with the base of jets in AGNs is studied. Considering reasonable cloud and jet parameters, we estimate the relevant dynamical timescales of these interactions, concluding that clouds can enter into the jet only above a certain height,  $\sim z_{\text{int}}$ . Below  $z_{\text{int}}$ , the jet is too compact and its ram/magnetic pressure will destroy the cloud before fully penetrating into the jet. Once the cloud significantly interacts with the jet, strong shocks are generated and gamma rays can be produced with an efficiency that depends strongly on the bow-shock magnetic field.

Bow shock  $B$ -values well below equipartition with non-thermal particles allow significant gamma-ray emission. For very high  $B$ -values (Poynting-flux dominated jets), the treatment performed here does not apply. In that case,  $z_{\text{int}}$  could be still defined adopting the jet magnetic pressure instead of the ram pressure. If a cloud entered in such a jet, particle acceleration in the bow shock could still occur due to, for instance, magnetic reconnection. The study of such a case would require a completely different approach than the one presented here. In general, for bow-shock magnetic fields above equipartition with non-thermal particles, the IC channel and gamma ray production will be suppressed in favor of synchrotron emission. Unless magnetic dissipation reduced the magnetic field enough for IC to be dominant. Bow shock  $B$ -values well below equipartition with non-thermal particles allow significant gamma-ray emission. We note that modeling of gamma rays from AGN jets uses to require relatively low magnetic fields (e.g. Ghisellini et al. 2010). Therefore, it could be that, even if the jet magnetic field were high at  $z_{\text{int}}$ , it could become small enough farther up due to bulk acceleration (e.g. Komissarov et al. 2007) or some other form of magnetic dissipation.

For very nearby sources, like Cen A, the interaction of big clouds with jets may be detectable as a flaring event, although the number of these big clouds and thereby the duty cycle of the flares are difficult to estimate. Given the weak external photon fields in these sources, VHE photons can escape without suffering significant absorption. Therefore, jet-cloud interactions in nearby FR I may be detectable in both the HE and the VHE range as flares with timescales of about one day. Studying such a radiation would provide information on the environmental conditions and the base of the jet in these sources.

In FR II sources, many BLR clouds could interact simultaneously with the jet. The number of clouds depends strongly on the cloud lifetime inside the jet, which could be of the order of several  $t_{\text{cs}}$ . Nevertheless, it is worthy noting that after cloud fragmentation many bow shocks can still form and efficiently accelerate particles if these fragments are slower than the jet. Since FR II sources are expected to present high accretion rates, radiation above 1 GeV produced in the jet base can be strongly attenuated due to the dense disc and the BLR photon fields, although gamma rays below 1 GeV should not be significantly affected. Since jet-cloud emission should be rather isotropic, it would be masked by jet beamed emission in blazar sources, although since powerful/nearby FR II jets do not present significant beaming, these objects could indeed show gamma rays from jet-cloud interactions. In the context of AGN unification (Urry & Padovani 1995), the number of non-blazar (radio-loud) AGNs should be much larger than that of blazars

with the same  $L_j$ . As shown in Fig. 5, close and powerful sources could be detectable by deep enough observations of *Fermi*. After few-years exposure a significant signal from these objects could arise, their detection providing strong evidence that jets are already strongly matter dominated at the bow shock regions, as well as physical information on the BLR and jet base region.

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